DESIGNING FINE BITUMINOUS MIXTURES FOR HIGH SKID RESISTANCE

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by

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Technical Paper

TO: K. B. Woods, Director
Joint Highway Research Project

January [illegible]

FROM: H. L. Michael, Assistant Director
Joint Highway Research Project

File: 9-6-10
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Attached is a technical paper entitled, "Designing Thin Bituminous Mixtures for High Skid Resistance". This paper has been prepared by Professor Jack H. Stephens, formerly of our staff, and Professor William H. Goetz of our staff. The paper was prepared for presentation at the 39th Annual Meeting of the Highway Research Board.

This paper summarizes a study that was undertaken in an attempt to evaluate the variables that affect the skid resistance of fine bituminous mixes. A number of important conclusions are included.

This paper will be submitted to the Highway Research Board for possible publication. It is presented to the Board for release for such publication and for the record.

Respectfully submitted,

Harold L. Michael

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Secretary

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DESIGNING FINE BITUMINOUS MIXTURES

for

HIGH SKID RESISTANCE

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INTRODUCTION

Since the advent of the modern motor vehicle, many investigators have shown a relationship between the skid resistance of the pavement and the accident rate of the roadway. The importance of this problem has been substantially increased by both the intensity and the speed of modern traffic, and the skid resistance or friction between pavement and tires has been studied extensively in recent years. Many pavements which a few years ago had sufficiently high skid resistance, have now become problem pavements (3).

Increasing the speed of traffic over a given roadway, without improvement in alignment or other physical features, will create a need for greater skid resistance. If the skid resistance of the pavement was barely adequate at the lower speed, it is possible that it will be insufficient at the higher speed, and a dangerous pavement will exist. The increased volumes of traffic operating over the highways have contributed to this slipperiness problem by accelerating the rate at which the aggregate in the pavement surface polishes (4).

Deslicking programs are gaining headway in several states (2). A satisfactory treatment must provide adequate skid resistance at an economically feasible initial cost, and some thought should be given to the length of time for which the surface will retain a high degree of skid resistance. Any practical program of deslicking pavements must give due consideration to planning new pavement mixes that with time do not polish to such a degree that they must be treated. In a region where older pavements have polished, it is to be expected that new pavements will do likewise unless steps are

taken to alter the mix used for the wearing surface to include design criteria that will preclude extreme polishing.

It appears that the practical and economical approach to this problem in many areas involves the use of locally available sands in fine-aggregate types of mixes. However, all fine mixes are not necessarily skid resistant nor are the most skid-resistant types of fine aggregate, and gradations of them, available in all areas. Therefore, this study was undertaken in an attempt to evaluate mix variables that affect the skid resistance of fine bituminous mixes.

LABORATORY TEST PROCEDURE

The first step in evaluating the effect of mix variables on the skid-resistance characteristics of fine mixes must be that of determining a method of procedure for comparing the different mixtures. It is probable that one of the several methods of full-scale field skid testing provides conditions most nearly approaching those present during normal wet-weather vehicle operation. However, within each of these methods certain physical quantities cannot be readily controlled. Highway design factors must be used as found and the weather history immediately prior to test frequently varies from test to test (3). With respect to the field method of measuring skid resistance, a major disadvantage of the stopping-distance method is the inherent inability to measure skid resistance on horizontal or vertical curves of pavements, which may well be the locations where maximum polishing occurs. Towed wheels of either the American trailer type or the European skewed-wheel type permit testing at nearly any location (4), but both of these types of equipment have a high initial cost.

To evaluate mix variables and to design skid-resistant pavements by the utilization of skid tests applied to trial mixes requires laboratory testing. The use of automotive-type equipment in the laboratory requires the construction of sample pavements large enough for realistic skids. The use of such large samples would circumvent the problem of scale factor, but in turn would introduce an economic factor. The cost of carrying out even a limited series of tests involving a single design variable would be great. If the polishing effect of traffic is to be included, the time required for such polishing to occur may incur prohibitive delays in completing the tests.

In order to study surface factors that affect skid resistance, a laboratory method of skid testing has been developed by the Joint Highway Research Project at Purdue University (6). This machine was first applied to the problem of measuring the relative skid resistance of coarse-aggregate pavements and more recently to the skid resistance of sand mixes. The initial skid resistance of laboratory mixes and that remaining after several years of simulated traffic polish, were measured. An accelerated polishing procedure was used.

For this initial study into mix design as applied to skid resistance of fine mixes, the more obvious factors such as gradation, particle shape, and mineral composition were investigated. All test results presented and discussed in this paper are for fine bituminous mixtures.

Skid - Test Procedure

The laboratory skid machine available at Purdue University was used for this study. As this machine was originally used with coarse materials (6), some modifications were found desirable (3). The machine as used,

Figs. 1 and 2, consisted of a vertically mounted mandrel with a chuck to carry a pavement sample, a power unit to rotate the mandrel, a rubber test shoe, a loading system for the test shoe, and a system of measuring and recording the friction developed between the test shoe and the pavement sample.

The power unit rotated the mandrel at a speed of 2500 rpm. The circular pavement samples when clamped in the chuck rotated with the mandrel. The rubber test shoe, Fig. 3, was made from a block of tire-tread rubber and had a radial pattern of slots. These slots were necessary in order to permit the application of water to the surface during the test and did not represent the tread on a tire. Attempts at dry skidding resulted in extreme temperature rises of both the pavement and the rubber shoe and thus misleading values for friction. All tests were performed with liberal amounts of water applied to the sample surface.

A load beam and weights were used to apply a normal force to the rubber shoe of a magnitude which corresponded to the normal pressure between passenger car tires and highway pavement. When not skidding, the beam, weights, and test shoe were held up by an air cylinder. For each test the specimen was allowed to come to speed, the water supply was turned on, and the pressure was bled from the cylinder at such a rate as to permit building up the test load on the shoe in a one-second interval. The loaded shoe was held against the spinning bituminous specimen for two seconds and then removed, giving a total testing cycle of three seconds. After a two-second pause, the loading cycle was repeated and the frictional resistance at the mid-point of the second skid was reported as the relative resistance value.

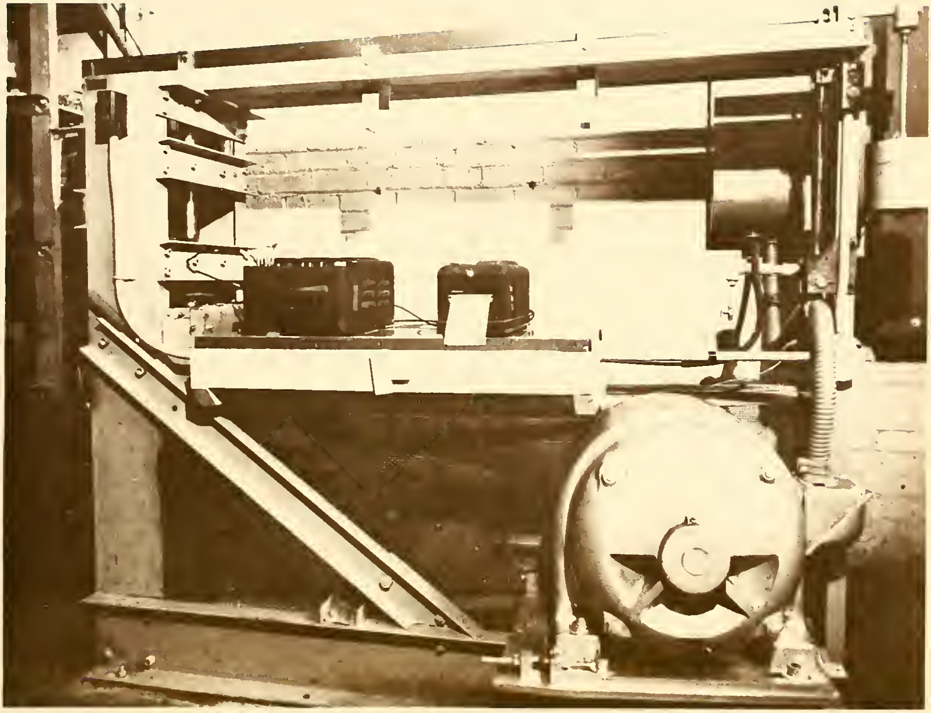


FIG. I LABORATORY SKID RESISTANCE MACHINE

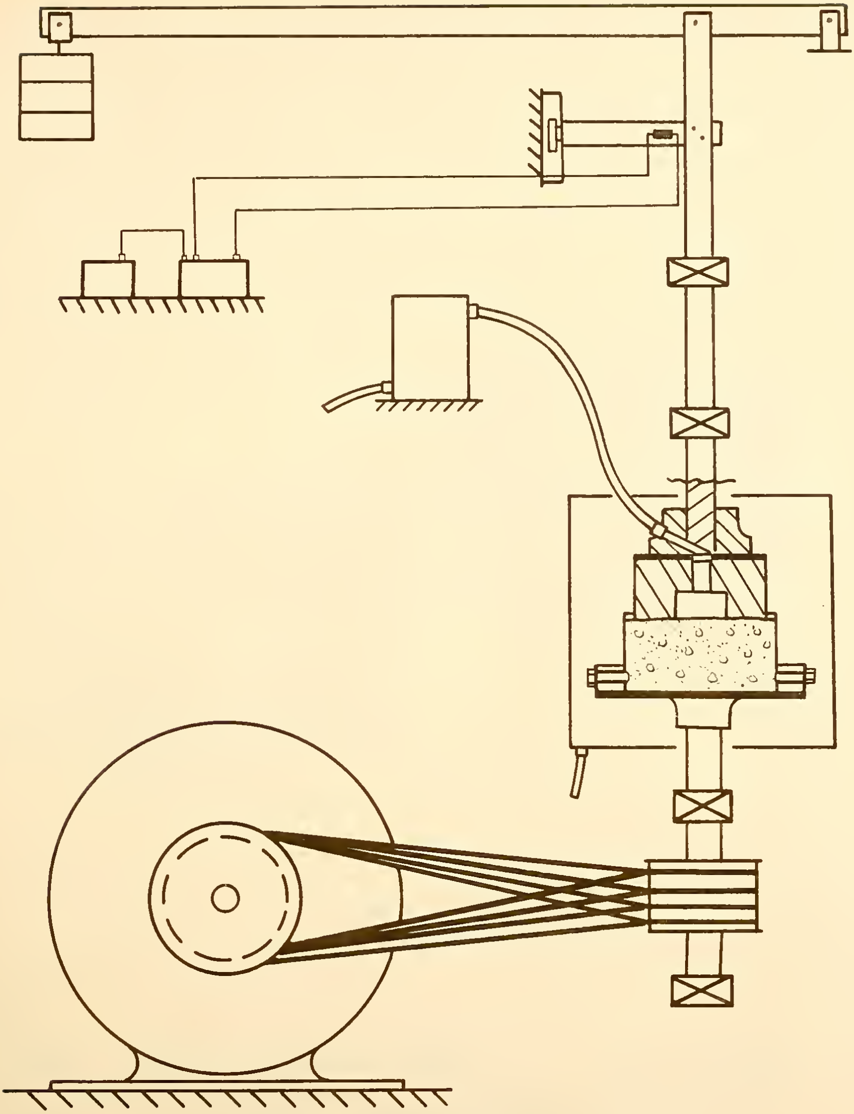


FIG. 2 SCHEMATIC DIAGRAM OF LABORATORY SKID-TEST APPARATUS

FIG. 3 TEST SHOES USED IN THE LABORATORY SKID RESISTANCE MACHINE

This relative resistance value is, in actuality, a relative frictional torque transmitted by the rotating specimen to the floating test shoe. The test shoe was mounted on a ball-bearing shaft or mandrel colinear with that carrying the specimen, and was restrained from turning by a cantilever bar on which were located SR-4 strain gages. Any tendency for the test shoe to rotate was then reflected in the reading on the attached Brush analyzer. The analyzer recorded frictional torque and as the distribution of the frictional stresses across the circular contact area of the test shoe is unknown, these readings have been left as relative resistance values.

The pavement samples as molded were six inches in diameter. The test shoe had an outside diameter of five and one half inches and an inside diameter of three inches. The radial slots across the shoe were 3/16 inch wide and 3/16 inch deep. The relative tangential velocity at the average radius of the test shoe approximated 30 mph. The tangential velocity at the inner edge of the test shoe was 18.5 mph and that at the outer edge 41.5 mph. The normal pressure of the shoe on the pavement during testing was 28 psi.

Preparation of Pavement Samples

The raw, fine aggregate of each type was dried and sieved into size fractions. For each mix, the desired proportions of these size fractions were dry-batched by weight. The aggregate and the asphalt were heated in an oven to 325°F. The asphalt was then added to the aggregate and the material mixed in a small laboratory mixer. The resulting fine bituminous mixture was compacted in a ring mold under the action of a 500 lb. force applied to the surface through an air-operated vibrator as shown in Fig. 4. The molded specimens were then set aside to cool under room conditions until the surface temperature was 125°F. at which time the surface was rolled by

the use of small, conical steel rollers, Fig. 5, in the Miniwrack machine loaded to 25 pounds per inch of width. The first skid tests were performed on the day following the molding of specimens.

Polishing of Samples

It was felt that testing the specimens in an "as rolled" condition only could not foretell possible reduction in skid resistance due to the gradual polishing of the surfaces under the action of traffic. As an attempt to produce such a polished condition rapidly, each specimen was subjected to an accelerated polishing process. To prevent the development of a pattern of wear or polish on the surface, a compound motion of the polishing shoe was used. This was accomplished by placing the mold and specimen on a ball-bearing turntable, Fig. 6, which, in turn, rested on the table of a standard shop drill press. A small, round, rubber polishing shoe with a diameter somewhat greater than the width of the circular test surface was turned by the drill press chuck as shown in Fig. 7. With the turntable properly located, pressing the rotating polishing shoe against the pavement surface caused the pavement sample to rotate. This resulted in every point of the test area receiving polish from different directions and no discernable wear pattern developed. The polishing was further hastened by putting very fine abrasive dust (No. 000 crushed quartz for the first polish and No. 00000 for the second) in the water used to cool the surface during polishing (5). Slots cut across the polishing shoe aided circulation of the water and carried abrasive under the shoe. Four minutes of polishing gave 14,000 polishing segments passing over parts of the surface. Skid tests were repeated on each surface after each of two such four-minute polishing cycles. Additional repetitions of the polishing and testing procedure carried out on some of the specimens caused little further reduction in skid resistance.

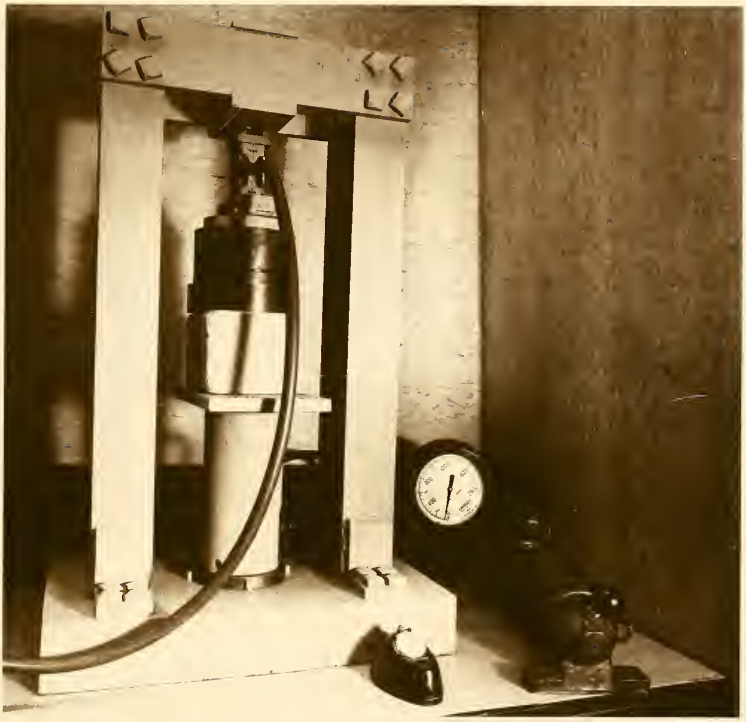


FIG. 4 EQUIPMENT FOR MOLDING LABORATORY SPECIMENS

FIG. 5 LABORATORY ROLLERS

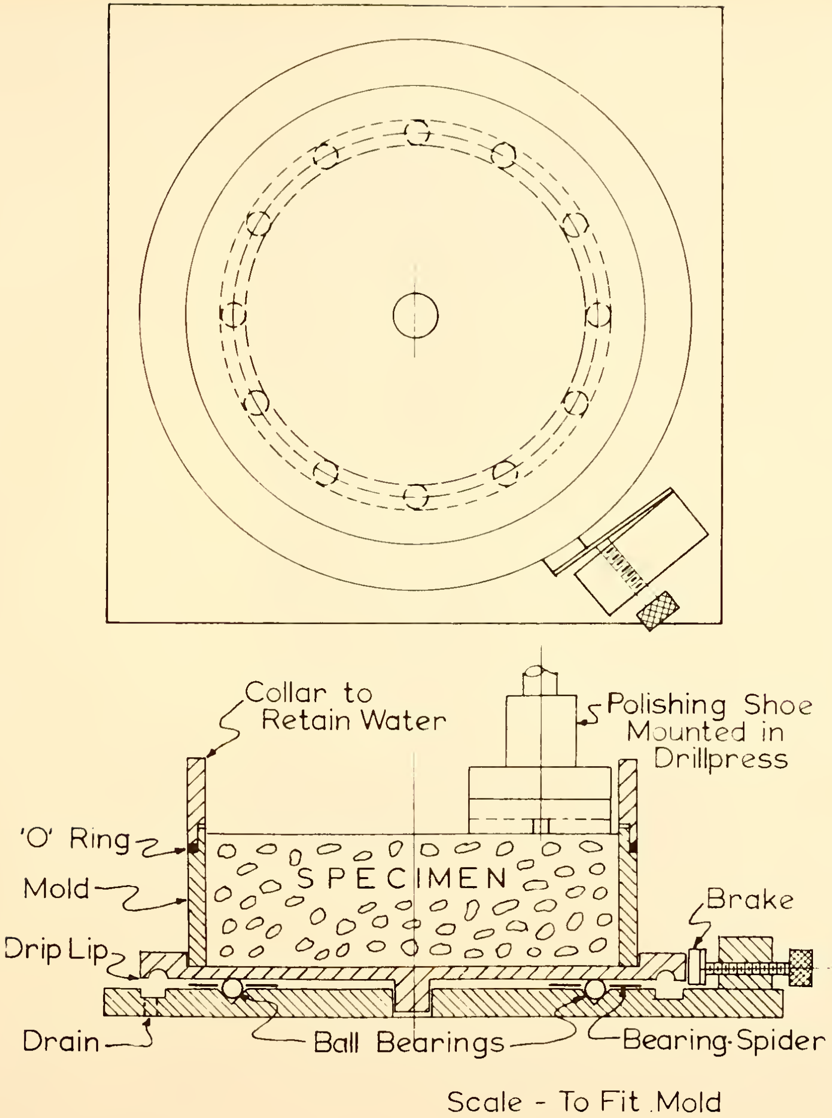


FIG. 6 . DIAGRAM OF POLISHING TURNTABLE

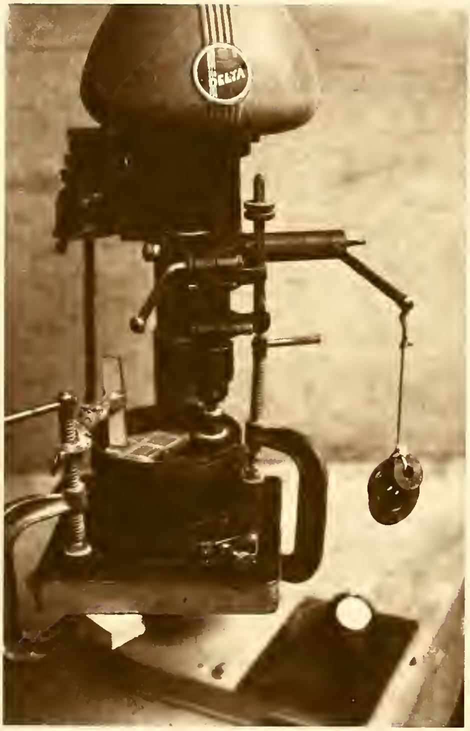


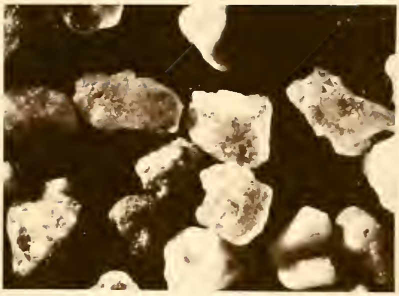
FIG. 7 DRILL PRESS SETUP FOR POLISHING

EFFECT OF MINERAL CONTENT ON SKID RESISTANCE

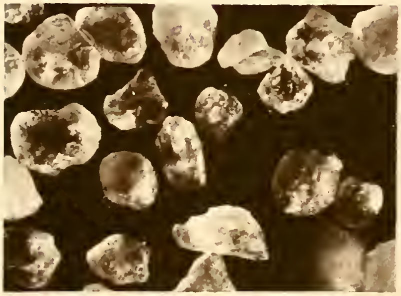
In most localities some variation in mineral composition of fine aggregate can be secured by careful choice of aggregate source. In order to take advantage of such a choice of material when designing permanent skid resistance into pavement mixes, the effect of mineral composition upon skid resistance must be evaluated.

For the purposes of this study, materials were used which might be utilized as aggregate in fine bituminous mixes made in Indiana. Through much of this area glacial sands have been used for fine mixes. These sands are quite variable with the mineral content being dependent upon location of the deposit sampled. Two representative sands of this kind were used. That from Lafayette, Indiana had 70% silica and 30% carbonates. That from Richmond, Indiana had 45% silica and 55% carbonates. These percentages will vary slightly with gradation as the mineral content varied with grain size. See Table 1. Silicates and carbonates were separated by soaking the aggregate in hydrochloric acid for 24 hours. The insoluble residue was reported as silicates and that part which dissolved as carbonates.

A natural sand from Chillicothe, Ohio was used as representative of high-silica sand. The silicate content of this aggregate was between 98 and 100% for all gradations. No natural low-silica sand was available, so crushed limestone was used which had been rounded by tumbling for 30,000 revolutions in a Los Angeles Rattler without using the steel balls. The silica content of this aggregate was between 1 and 5% for all gradations. Photomicrographs of these sands are shown in Fig. 8, and their physical and chemical test properties are given in Table 1.


LAFAYETTE SAND


RICHMOND SAND


SILICA SAND


CRUSHED SILICA SAND


CRUSHED AND ROUNDED
LIMESTONE SAND


LIMESTONE SAND

FIG. 8 GRAIN SHAPE AND TEXTURE
OF SIX SANDS (25 X)

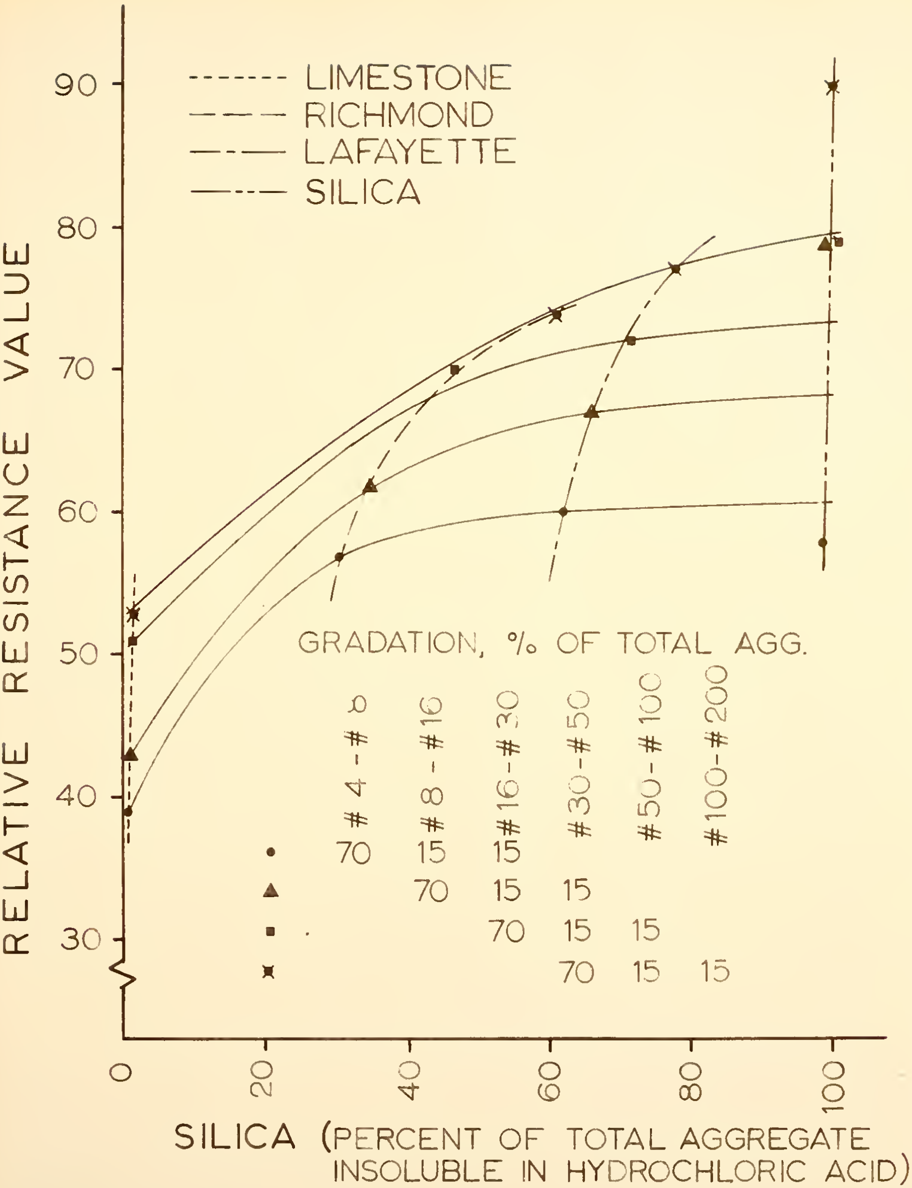


FIG. 9 VARIATION IN RELATIVE RESISTANCE VALUE FOR FINE BITUMINOUS MIXES WITH SILICA CONTENT OF FINE AGGREGATE

These four sands, Lafayette, Richmond, Silica (Chillicothe) and Limestone which had been crushed and worn, were tested for skid resistance at four different gradations as shown in Table 2 (Appendix) for the purpose of studying the effect of mineral composition. The relative resistance values obtained for these different materials are given in Table 2 and the values after the second polish are shown in Fig. 9. In this figure the abscissa is percent of silica in the aggregate and the ordinate is relative resistance value. The resulting points can be included in a band of relatively narrow width. The variation within this band at any silica content is due largely to gradation. This observation is based on the manner in which relative resistance values representing mixes of low fineness modulus fall in the top of the band and those representing high fineness modulus fall near the bottom.

The general shape of the band shows that in a blended material such as the glacial sand there is some increase in relative resistance value with silica content. The rate of increase is greatest at low silica contents. An exact point above which silica content becomes of little importance cannot be given as the importance is a relative matter. However, the relative resistance value did not change greatly for silica contents above that of the Richmond sand. It can be stated that the average relative resistance value of the four gradations used increased from 45 to 66 or nearly 47% as the aggregate changed from 0% silica, approximated by limestone, to 45% silica, approximated by Richmond sand. Changing from Richmond sand to Lafayette sand resulted in about one half of this change in silica content, but only a further increase in average relative resistance value of four units. The skid resistance of the silica sand mixes was substantially better than that of the Lafayette sand mixes but the results for the silica do not seem to fit the curves.

There would seem to be added factors that should be considered. Aggregate blended from Richmond sand and silica sand could be prepared with the same gradation and silica content as the Lafayette sand. The resulting sand could have a relative resistance value different from the Lafayette sand. The reasoning behind this statement is that discrete particles of two materials when mixed may not give the same surface character as particles with the same two materials existing within each particle. While all of the materials used were rounded in shape as opposed to being crushed, grain shape did vary to some degree. Also, as shown by Fig. 8, the surface texture of individual particles varied as well. The relative gradation of the individual materials might have an effect upon surface character. Dillard and Alwood (2) observed that blending non-polishing aggregate with poor aggregate was not always effective.

EFFECT OF AGGREGATE SHAPE ON SKID RESISTANCE

Aggregate particles exist in a range of shapes from that of well-rounded spheres to multi-sided angular particles. Many natural deposits of rounded material occur as glacial or aluvial sands and gravels. Angular material results from crushing oversize material or quarried rock. It is to be expected that material of every degree of sharpness between these two extremes exists. Logically, the use of sharp angular particles should aid in developing increased skid resistance. The sharp edges should bite into tire rubber better than round edges and the contact pressure would be higher, thus aiding in reduction of moisture on the areas of contact (3). Such logic should be verified by experimental means prior to incorporation into pavement design.

In order to determine the degree to which particle shape determines the relative resistance value for fine bituminous mixes, results of skid resistance tests on round aggregate were compared to those on angular aggregate. Natural silica sand was compared to angular silica sand prepared by crushing coarse fractions of the same silica sand. Angular limestone sand from a commercial source was compared to the same limestone sand rounded by tumbling 30,000 revolutions in a Los Angeles Rattler with the steel balls removed. These materials are shown in Fig. 8.

The gradations and resultant relative resistance values for the mixes used in this phase of the investigation are shown in Table 2. As the relative effect of shape was not the same for the two materials used, the results have been plotted separately as Figs. 10 and 11. As shown by Fig. 10, the angular silica sand appears substantially superior to the rounded sand when tested in an as rolled condition. The amount of this superiority in skid resistance decreased as the size of the particles was reduced until at the finest size used the round material was superior to the angular. When tested after two polish cycles the relative resistance value of the angular sand had fallen down to and even below that for the round silica sand.

It should be noted that the same amount of polishing which lowered the relative resistance value of the angular-sand mixes so drastically, did not appreciably raise or lower that of the round-sand mixes. This is significant as the indications are that the angular edges do raise the skid resistance, but that polishing or wearing of the edges quickly removes their effectiveness (3). Even a hard aggregate such as silica cannot retain, for long, skid resistance due primarily to angular particle edges.

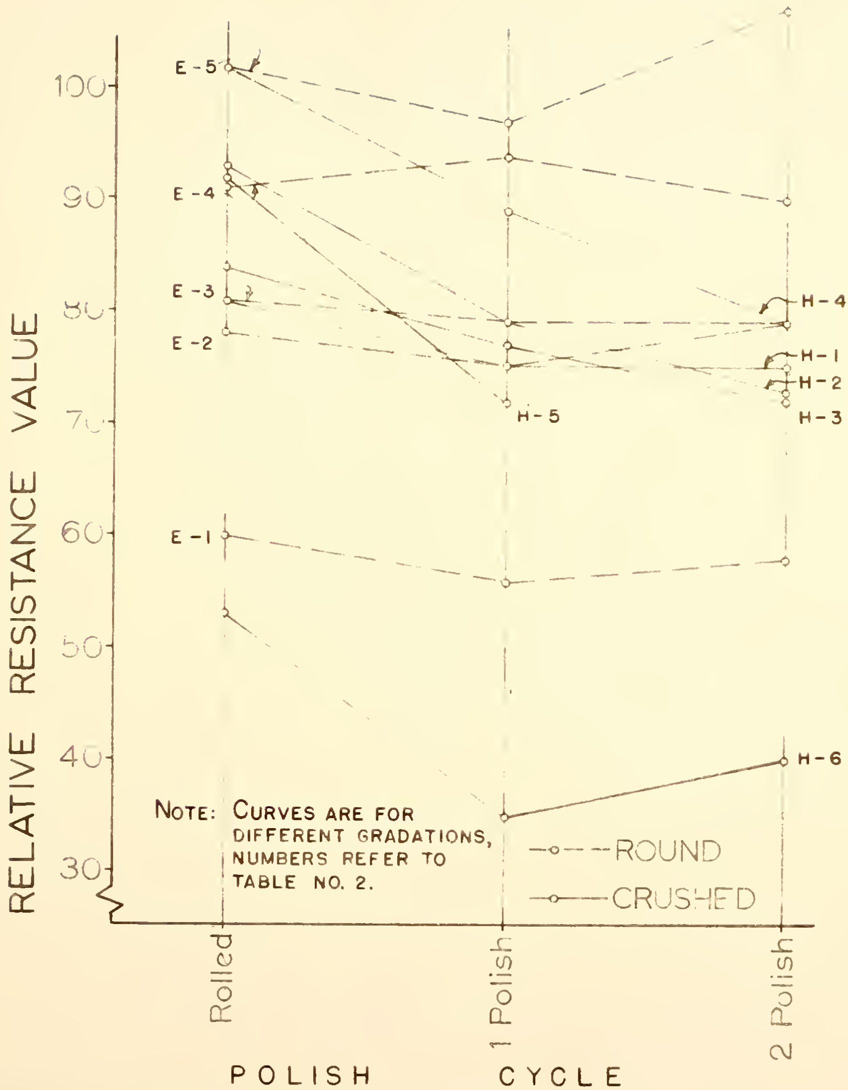


FIG. 10 VARIATION IN SKID RESISTANCE WITH POLISHING CYCLE FOR FINE BITUMINOUS MIXTURES COMPOSED OF ROUND AND ANGULAR SILICA SAND

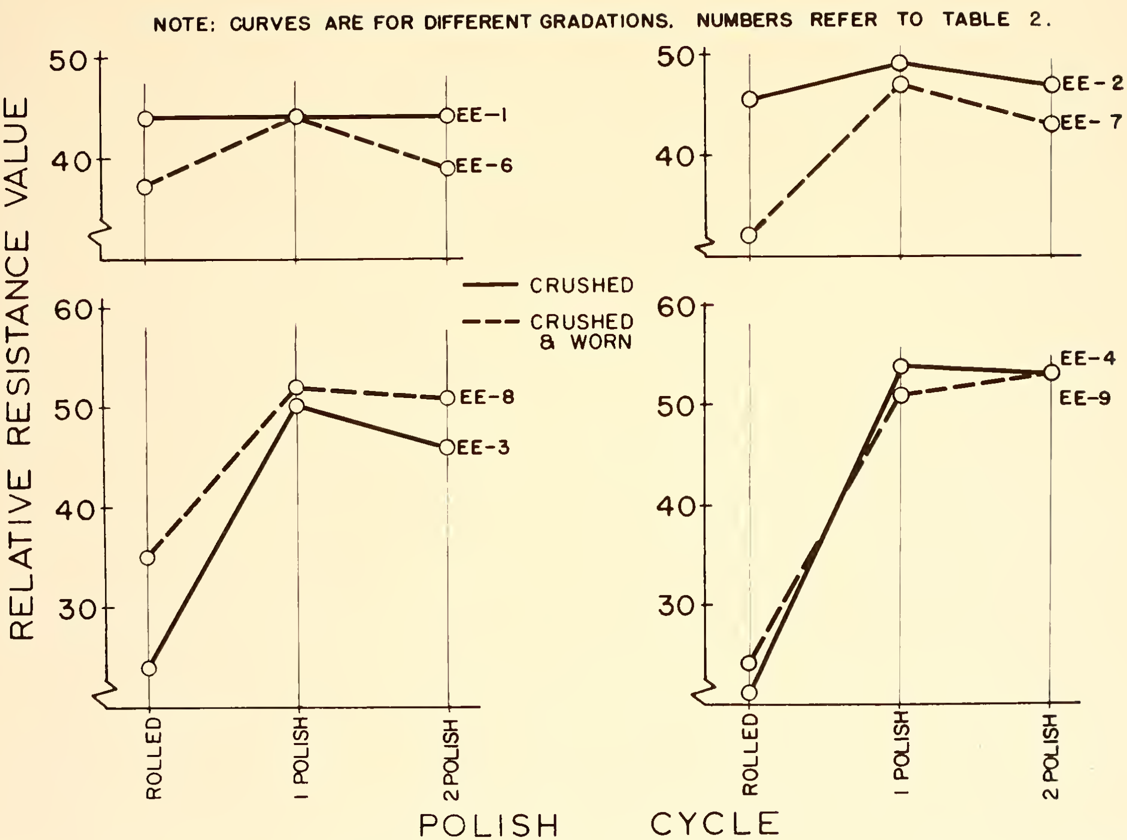


FIG. 11 VARIATION IN SKID RESISTANCE WITH POLISHING CYCLE FOR FINE BITUMINOUS MIXTURES COMPOSED OF ROUND AND ANGULAR LIMESTONE SAND

As shown by Fig. 11, the limestone sands did not demonstrate any appreciable shape effect. In two out of four cases, initial skid resistance results for the rounded aggregate are greater than for the angular material. This lack of shape effect can be explained as the cumulative result of two characteristics of the material. An inspection of Fig. 8 reveals that the limestone crushes into a less angular form than the silica. Also, the limestone is softer than the silica and wears away quickly. The first column of relative resistance values recorded in Table 2 are the readings from the oscillograph tape at the middle of the second test skid. At this time, 3,335 rubber edges have passed over every point in the test surface. It is possible that the soft limestone edges had worn to a degree equal to that of the rounded limestone before the first relative resistance values were recorded. Under these conditions round or angular limestone aggregates would result in the same relative resistance values.

There are, then, two major effects of particle shape upon skid resistance. The first can be considered as a general relationship with most angular aggregate giving higher relative resistance values. The second effect is concerned with a change in the rate of polish of pavement surfaces. A large increase in skid resistance gained by crushing aggregate in order to secure angular particles may be of short duration. Apparently the more angular the particles, the more rapid the rate of polish. As angularity varies with hardness of the aggregate, the importance of the shape factor varies with the material as well as with particle size.

EFFECT OF GRADATION ON SKID RESISTANCE

The principle of surface texture controlling skid resistance focuses attention on aggregate particle size. A pavement made of large pieces of cut stone would have a surface texture determined by the texture of the aggregate surface itself. A pavement made of many sizes of extremely fine aggregate would have the surface texture of the aggregate mixture (1). Most practical pavements fall between these two extremes with the importance of aggregate gradation to the surface texture increasing as the aggregate becomes finer.

The results of skid-resistance tests conducted on mixes employing different gradations of aggregate sand are shown in Table 5. These results have been plotted in Figs. 12 and 13. In Fig. 12 the relative resistance value has been correlated with fineness modulus. Attempts to correlate the results of all mixes by means of a single curve were not satisfactory. Using the mixes in groups of similar maximum size aggregate gives the family of curves plotted in this figure. These curves, which were fitted independently by the method of least squares, are in very good agreement. The slopes of three are nearly identical and that of the other two are only slightly different. It is possible that more exact control of testing conditions might alter the test results enough that the slopes of all of the curves would be identical.

There is a definite trend for relative resistance values to increase as the fineness modulus increases. Also, there appears to be a maximum relative resistance value associated with each size of particle. When the gradation of the mix varied in such a manner as to make one size predominate, the resulting relative resistance value approached that associated with this size. This, then, suggests the possibility of correlating the relative resistance value with the size of particle present in the mix.

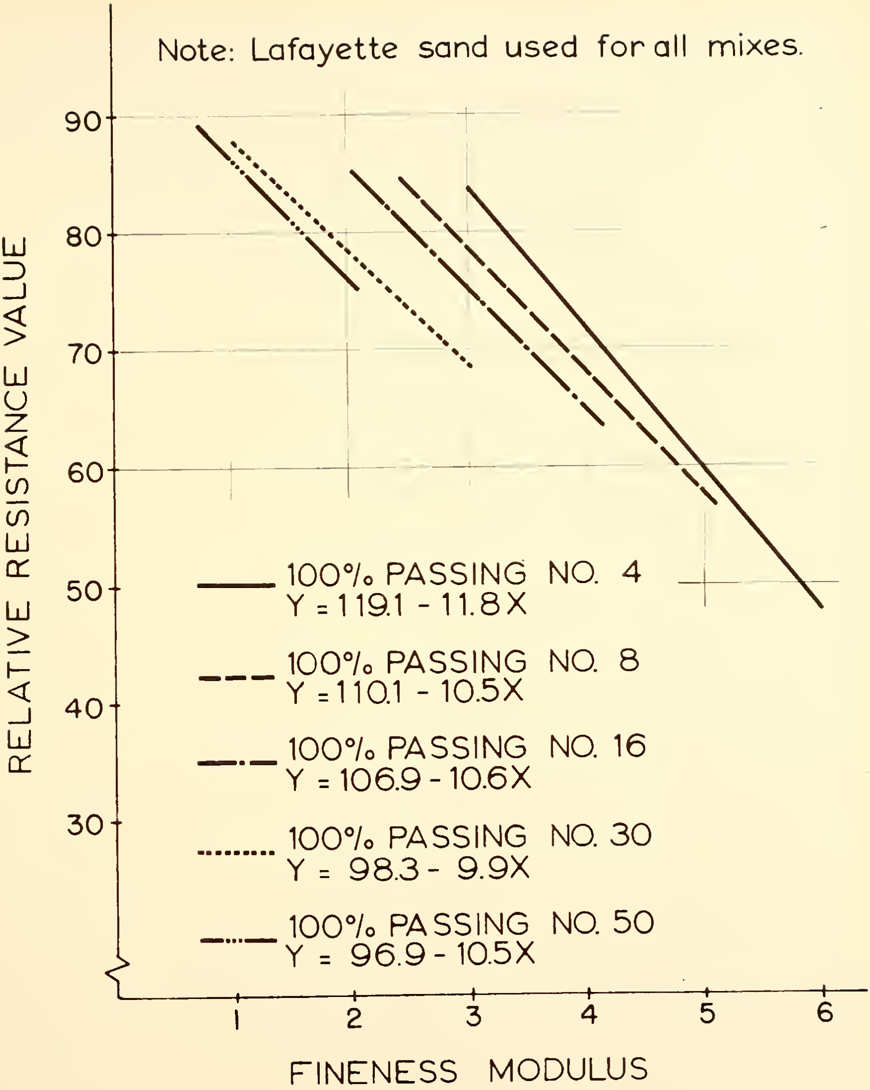


FIG. 12 VARIATION IN SKID RESISTANCE WITH FINENESS MODULUS FOR FINE BITUMINOUS MIXTURES

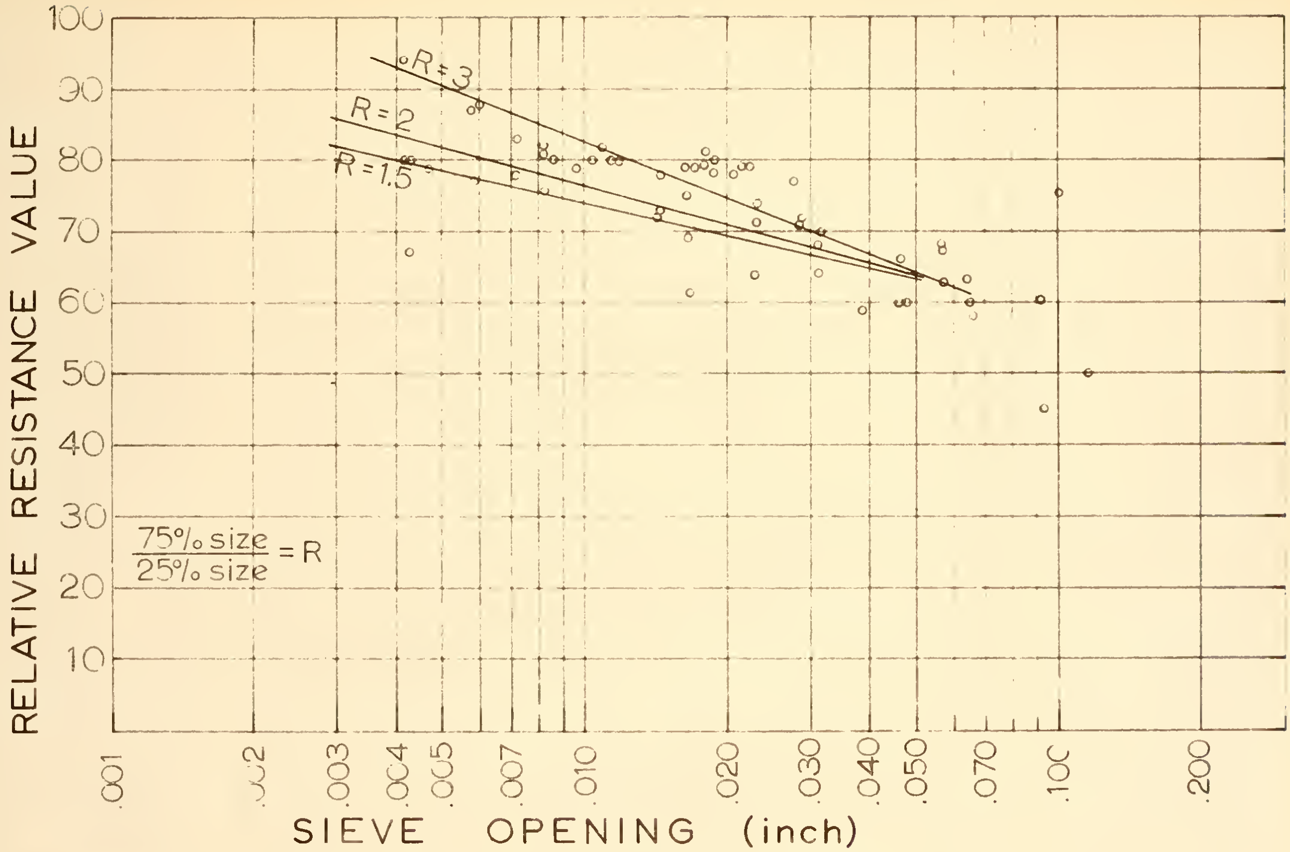


FIG. 13 VARIATION IN RELATIVE RESISTANCE VALUE WITH 50% SIZE OF AGGREGATE (FINE BITUMINOUS MIXES)

For a given range of sizes within the mix, the percent of any one size required to make that size predominate or govern the resulting relative resistance value must vary. The position of the particle in the range of sizes present is the main factor in determining the percent needed for control. Fig. 13 has been prepared to show the correlation between the 50% size of the aggregate and relative resistance value.

Specifying only the 50% size permits a wide latitude of gradations. The ratio of the 75% size particles (75% finer than this size) to the 25% size has been used in Fig. 13 to define the spread of the gradation. Within the method of computation used, the minimum ratio of 75% size to 25% size approached 1.25 and was obtained for a gradation using 100% of material passing one sieve and retained on the next. At the other extreme, some of the gradations gave a ratio in the range of 6 to 8. Although the correlation is not perfect there is a definite trend for the low ratios to be in the lower side of the band and the higher ratios in the upper side. Instead of a single line, three lines representative of the ratios covering a reasonable range of gradations are shown.

A ratio of one indicates uniform size particles and higher ratios are for increasingly wide-spread gradations. The longer gradations gave the best results. Computations show that a gradation with a ratio of 75% size to 25% size of two would have nearly twice the number of contact points between tire and pavement as a surface made from a gradation with a ratio of one.

The overall change in relative resistance values is large, but the band containing the experimental results is narrow. It is then apparent that the size factor is more important in determining skid resistance than the gradation.

Within the range of sizes included in Table 3, the relative resistance values continually decreased as the 50% size was reduced. It would seem that an optimum size must exist, as infinitely small particles would give a surface with no measurable surface texture and a minimum skid resistance. Limited tests on even finer mixtures indicated the optimum size of particles to be approximately 0.009 inch diameter. Difficulties were encountered in sieving sufficient material finer than a No. 100 sieve from the Lafayette sands. The fine mixes also required excessive asphalt contents and were hard to mix.

CONCLUSION

This laboratory study has produced a number of important conclusions. However, they have not been verified by field tests and it is entirely possible that differences between laboratory and field conditions may require that these conclusions be modified for application to pavement surfaces. Within the limitations of the test procedures and for the range of materials and conditions utilized, the following conclusions are considered valid.

The skid resistance of fine bituminous mixtures, as measured by relative resistance values, is dependent upon many physical and chemical properties of the aggregate. The chemical composition or mineral content of the aggregate has an appreciable effect. The test results reported in this paper indicate that carbonates give low relative resistance values and that silicates give high values. The relationship is not in the form of a straight line. Changing from an aggregate with +95% carbonates to one of ± 45% silicate, ± 55% carbonate content brought about a large improvement in the relative resistance value. However, changing to ±75% silicate aggregate resulted in only a minor further increase in relative resistance value.

This, then, implies that as the carbonate content of the aggregate decreases, the skid resistance increases. However, the rate of increase is continually decreasing as the carbonate content decreases. It can then be concluded that the silica content is important in creating skid resistance when the carbonate content is high. At carbonate contents below approximately 50%, small changes in mineral content do not result in appreciable changes in skid resistance.

The shape of aggregate particles is hard to control, but does effect the skid resistance of a fine bituminous mix. The test results show two distinct effects resulting from variations in the shape of aggregate particles used. Comparison of relative resistance values for round and angular shapes of the same material reveals an initial superiority for the angular material in most instances. However, under the polishing action of the rubber shoe driven by the drill press, the surfaces made from angular particles polished rapidly. The skid resistance of the surfaces made of round particles remained nearly constant regardless of the polishing effort expended upon them.

It can then be concluded that highly skid-risistant surfaces can be created from angular particles. However, this high resistance may be temporary as surfaces for which a high resistance value was obtained by angularity will polish readily. The skid resistance of angular mixtures will decrease until below that of a surface made from well-rounded particles of the same material.

The size of particles used as aggregate in fine bituminous mixes has a major effect upon skid resistance. Within the range of this study it appears that the finer the particles used in a bituminous mix, the greater the resulting relative resistance values. For any particular average size particle, the mixes with a range of sizes permitting a ratio of 75% size to 25% size between 2 and 6 consistently gave relative resistance values above the average.

It is concluded that gradations with a range of particle sizes are more skid resistant than uniform-size mixes. Fine aggregate which is to give the utmost in skid resistance should be chosen carefully. The particles should be fine, if possible in the range of 0.01 - 0.006 inch. The gradation should have a range such that the diameter of the coarsest particles are approximately 3 times that of the finest. This is intended to insure that the 75% size will be approximately twice the 25% size. The exact mineral content is not important but the silica content should be above the 40-50% level. For long range skid resistance, round particles will be as satisfactory as angular ones.

It is realized that the results presented here are from laboratory skid tests and should be further verified by field tests.

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Table 1. Results of Physical and Chemical Tests of Sands

Designation	Lafayette	Richmond	Silica	Limestone
Source	W. Lafayette, Ind.	Richmond, Ind.	Chillicothe, O.	Greencastle, Ind.
Type	Glacial Sand (Terrace)	Glacial Sand (Terrace)	Tertiary	Crushed Limestone
Bulk Specific Gravity	2.57	2.58	2.57	2.60
Apparent Specific Gravity	2.66	2.66	2.60	2.72
Absorption, %	1.57	1.13	0.47	1.97
Percent of material insoluble in hydrochloric acid by size fraction				
#4 - #8	52.9	29.0		0.7
#8 - #16	61.9	28.0	99.5	0.8
#16 - #30	68.7	38.3	99.6	1.0
#30 - #50	75.0	59.4	99.5	1.5
#50 - #100	88.2	70.0	99.3	3.5
#100 - #200	83.4	58.0	97.6	3.5
#200 - Finer	63.7	37.0	97.9	5.1

Table 2. Results of Skid Resistance Tests on Fine Bituminous Mixes Using Aggregates of Different Mineral Composition & Shape

Specimen	Sand Designation	Gradation, % of Total Aggregate						% of Blend Insoluble	Fineness Modulus	Asphalt, % of Aggregate	Relative Resistance Value		
		#4 - #8	#8 - #16	#16 - #30	#30 - #50	#50 - #100	#100 - #200				As Rolled	1 Polish	2 Polish
GG-1	Lafayette	70	15	15				62.4	5.55	5 1/2	47	55	60
GG-2			70	15	15			65.5	4.55	6	58	69	67
J-3				70	15	15		71.7	3.55	6 1/2	83	78	73
C-10					70	15	15	78.2	2.55	7	55	77	78
GG-6	Richmond	70	15	15				30.2	5.55	5 1/2	44	54	57
GG-7			70	15	15			34.2	4.55	6	57	67	62
GG-8				70	15	15		46.4	3.55	6	49	77	70
GG-9					70	15	15	60.9	2.55	6 1/2	65	79	74

Table 2. –Continued

Specimen	Aggregate	Shape	Gradation, % of Total Aggregate						Fineness Modulus	Asphalt, % of Aggregate	Relative Resistance Value		
			#4 - #8	#8 - #16	#16 - #30	#30 - #50	#50 - #100	#100 - #200			As Rolled	1 Polish	2 Polish
EE-1	Greencastle Limestone	Crushed	70	15	15				5.55	6	44	44	44
EE-2				70	15	15			4.55	6	43	49	45
EE-3					70	15	15		3.55	6	24	50	46
EE-4						70	15	15	2.55	7	21	54	53
EE-6		Crushed & Worn	70	15	15				5.55	6	37	44	39
EE-7				70	15	15			4.55	6	32	47	43
EE-8					70	15	15		3.55	6	35	52	51
EE-9						70	15	15	2.55	7	24	51	53

Table 2, --Concluded

Specimen	Aggregate	Shape	Gradation, % of Total Aggregate									Fineness Modulus	Asphalt, % of Aggregate	Relative Resistance Value		
			#4 - #8	#8 - #16	#16-#30	#30-#50	#50-#100	#100-#200	#200-Finer	#000 Quartz	#00000 Quartz			As Rolled	1 Polish	2 Polish
H-1	Silica Sand	Natural	70	15	15							5.55	6 1/2	60	56	58
H-2				70	15	15						4.55	6 1/2	77	75	79
H-3					70	15	15					3.55	6 1/2	81	79	79
H-4						70	15	15				2.55	7 1/2	91	94	90
H-5							70	15	15			1.55	8 1/2	102	97	108
E-1		Crushed	70	15	15							5.55	6	81	75	75
E-2				70	15	15						4.55	6	84	77	72
E-3					70	15	15					3.55	6 1/2	93	79	73
E-4						70	15	15				2.55	7	102	69	79
E-5							70	15		15		1.55	7 1/2	92	73	108
E-6								70		15	15	0.70	10	53	35	40

Table 3. Results of Skid Resistance Tests on Gradation Series of Fine Bituminous Mixes

Specimen	Gradation of Lafayette Sand % of Total Aggregate							Gradation Factors				Fineness Modulus	Asphalt, % of Aggregate	Relative Resistance Values		
	#4 - #8	#8 - #16	#16 - #30	#30 - #50	#50 - #100	#100 - #200	#200 - Finer	Diameter 25% Size	Diameter 50% Size	Diameter 75% Size	75% Size / 25% Size			As Rolled	1 Polish	2 Polish
J-1	70	15	15					.075	.118	.150	2.0	5.55	6½	66	58	60
J-2		70	15	15				.042	.058	.074	1.77	4.55	6½	72	67	66
J-3			70	15	15			.019	.029	.037	1.98	3.55	6½	73	71	72
J-4				70	15	15		.011	.015	.018	1.72	2.55	7½	83	78	73
J-5					70	15	15	.005	.007	.009	1.75	1.55	8½	104	94	83
F-1	50	25	25					.047	.094	.135	2.89	5.25	6	49	58	45
F-2		50	25	25				.023	.047	.067	2.91	4.25	6	59	66	60
F-3			50	25	25			.012	.023	.033	2.75	3.25	6½	72	81	64
F-5					50	25	25	.003	.006	.008	2.8	1.25	7½	86	110	88
F-6				100				.014	.017	.020	1.39	3.00	7	65	63	61
F-7					100			.008	.008	.010	1.26	2.00	7½	85	78	76
F-8						100		.004	.004	.005	1.43	1.00	9	110	95	67
F-9							100	.002	.002	.002	1.44	0	13	7	19	28

Table 3. — Continued

Specimen	Gradation of Lafayette Sand % of Total Aggregate							Gradation Factors				Fineness Modulus	Asphalt, % of Aggregate	Relative Resistance Values		
	#4 - #8	#8 - #16	#16 - #30	#30 - #50	#50 - #100	#100 - #200	#200 - Finer	Diameter 25% Size	Diameter 50% Size	Diameter 75% Size	75% Size / 25% Size			As Rolled	1 Polish	2 Polish
B-1	30	35	35					.038	.065	.105	2.76	4.95	6	58	65	63
B-2		30	35	35				.018	.032	.054	3.06	3.95	6½	63	70	70
B-3			30	35	35			.010	.017	.027	2.76	2.95	7	78	80	79
B-4				30	35	35		.005	.009	.013	2.71	1.95	7	90	84	80
B-5					30	35	35	.002	.004	.007	2.75	.95	7½	104	92	94
B-6	15	15	70					.03	.039	.059	1.97	4.45	6	49	60	59
B-8			15	15	70			.008	.010	.015	1.94	2.45	7	80	75	79
B-9				15	15	70		.004	.005	.008	2.0	1.45	8	84	70	79
C-7	70	15	15					.075	.118	.150	2.0	5.55	6	47	49	50
C-8		70	15	15				.042	.058	.074	1.77	4.55	6	53	63	63
C-9			70	15	15			.019	.029	.037	1.97	3.55	6	53	68	70
C-10				70	15	15		.011	.015	.018	1.72	2.55	7	55	77	78
C-11					70	15	15	.005	.007	.009	1.75	1.55	8	39	70	78

Table 3. — Continued

Specimen	Gradation of Lafayette Sand % of Total Aggregate							Gradation Factors				Fineness Modulus	Asphalt, % of Aggregate	Relative Resistance Values		
	#4 - #8	#8 - #16	#16 - #30	#30 - #50	#50 - #100	#100 - #200	#200 - Finer	Diameter 25% Size	Diameter 50% Size	Diameter 75% Size	75 % Size / 25% Size			As Rolled	1 Polish	2 Polish
AA-1	15	70	15					.052	.067	.085	1.64	5.00	6	53	57	58
AA-2		15	70	15				.026	.033	.042	1.63	4.00	6	57	70	68
AA-3			15	70	15			.013	.017	.021	1.65	3.00	6½	64	75	74
AA-4				15	70	15		.007	.008	.011	1.60	2.00	7	80	82	82
AA-5					15	70	15	.003	.004	.005	1.69	1.00	7	84	76	80
AA-6	25	50	25					.045	.066	.094	2.09	5.00	6	51	61	60
AA-7		25	50	25				.023	.033	.045	1.96	4.00	6	48	68	64
AA-8			25	50	25			.012	.017	.023	1.92	3.00	6½	56	77	75
AA-9				25	50	25		.006	.008	.012	2.0	2.00	7	74	84	81
AA-10					25	50	25	.003	.004	.006	2.0	1.00	7	77	108	80
BB-5	25	25	50					.033	.047	.094	2.85	4.75	6	58	63	60
BB-6		25	25	50				.017	.024	.045	2.72	3.75	6	60	73	71
BB-7			25	25	50			.008	.012	.023	2.74	2.75	6	66	84	80
BB-8				25	25	50		.004	.006	.012	2.86	1.75	6½	84	65	77

Table 3. -- Continued

Specimen	Gradation of Lafayette Sand % of Total Aggregate							Gradation Factors				Fineness Modulus	Asphalt, % of Aggregate	Relative Resistance Values		
	#4 - #8	#8 - #16	#16 - #30	#30 - #50	#50 - #100	#100 - #200	#200 - Finer	Diameter 25% Size	Diameter 50% Size	Diameter 75% Size	75% Size / 25% Size			As Rolled	1 Polish	2 Polish
CC-1	15	32½	35	17½				.027	.047	.076	2.81	4.45	5½	77	67	66
CC-2		15	30	30	25			.012	.021	.038	3.2	3.35	6	60	81	78
CC-3			12½	20	60	7½		.007	.011	.016	2.12	2.38	6½	84	86	80
CC-6	9		27	32	32			.01	.018	.031	3.1	3.22	6½	77	79	79
CC-7	18		24	29	29			.011	.019	.038	3.49	3.49	6	75	80	78
CC-8	27		21	26	26			.012	.022	.11	9.57	3.76	6	72	81	79
CC-9		18	24	29	29			.011	.019	.038	3.49	3.31	6	76	81	80
CC-10		27	21	26	26			.012	.022	.05	4.35	3.49	6	65	78	79
DD-1				100				.014	.017	.020	1.39	3.00	6	67	72	69
DD-4				50	25	25		.006	.012	.017	2.8	2.25	6½	84	81	80
DD-5	50	25	25					.047	.094	.134	2.89	5.25	5	59	63	60
DD-6					50	25	25	.003	.006	.008	2.76	1.25	7	87	89	87
DD-8	36		18	23	23			.013	.028	.115	9.2	4.03	6	71	81	77
DD-10	54		12	17	17			.016	.100	.137	8.56	4.57	5½	68	77	75

Table 3. -- Concluded

Specimen	Gradation of Lafayette Sand % of Total Aggregate							Gradation Factors				Fineness Modulus	Asphalt, % of Aggregate	Relative Resistance Values		
	#4 - #8	#8 - #16	#16 - #30	#30 - #50	#50 - #100	#100 - #200	#200 - Finer	Diameter 25% Size	Diameter 50% Size	Diameter 75% Size	75% Size / 25% Size			As Rolled	1 Polish	2 Polish
FF-3	5	10	15	50	20			.013	.018	.030	2.40	3.30	5½	66	81	81
FF-5		15	20	30	20	15		.008	.023	.033	3.93	3.00	6	70	75	74
FF-6	5	10	15	50	20			.013	.018	.030	2.40	3.30	5½	80	81	78
FF-9	5	10	15	50	20			.013	.018	.030	2.40	3.30	5½	68	81	79
GG-1	70	15	15					.075	.118	.150	2.0	5.55	5½	47	55	60
GG-2		70	15	15				.042	.058	.074	1.77	4.55	6	58	69	67
GG-3			70	15	15			.019	.029	.037	1.98	3.55	6	65	74	71
GG-4				70	15	15		.011	.015	.018	1.72	2.55	6½	76	80	72
GG-5			15	25	50	5		.008	.011	.018	2.36	2.65	7	78	84	82